

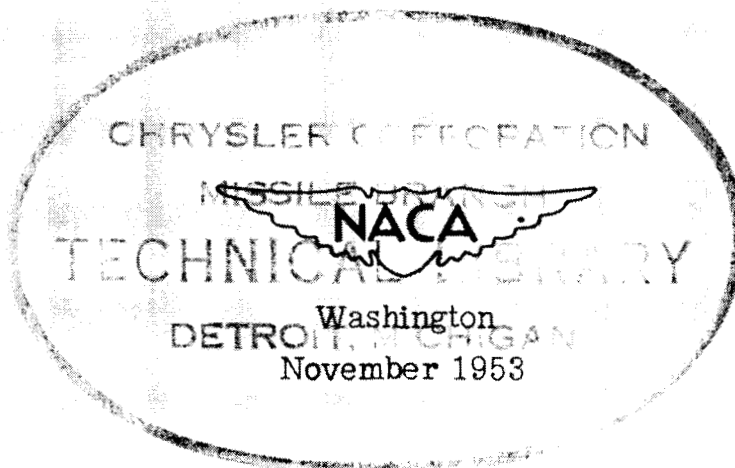
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM 1368

SUPERSATURATION IN THE SPONTANEOUS FORMATION
OF NUCLEI IN WATER VAPOR

By Adolf Sander and Gerhard Damköhler

Translation of "Übersättigung bei der spontanen Keimbildung in
Wasserdampf." Die Naturwissenschaften, vol. 31,
nos. 39/40, Sept. 24, 1943.



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I. STATEMENT OF THE PROBLEM

According to experience, a certain supersaturation is required for condensation of water vapor in the homogeneous phase; that is, for inception of the condensation, at a prescribed temperature, the water-vapor partial pressure must lie above the saturation pressure. The condensation starts on so-called condensation nuclei. Solid or liquid suspended particles may serve as nuclei; these particles may either a priori be present in the gas phase (dust, soot), or may spontaneously be formed from the vapor molecules to be condensed themselves. Only the second case will be considered below. Gas ions which facilitate the spontaneous formation of nuclei may be present or absent. The supersaturations necessary for spontaneous nucleus formation are in general considerably higher than those in the presence of suspended particles.

The condensed, thermodynamically stable phase pertaining to water vapor below 0° is the ice. According to all experiences so far, one must nevertheless assume in this temperature range the spontaneously formed primary particles to be predominantly liquid, in accordance with Ostwald's law of stages. The question is whether this is still valid at arbitrarily low temperatures, or whether not perhaps, after all, below a certain temperature the nuclei themselves already originate as (minute) crystals. This problem has so far been treated only theoretically² but not experimentally. Thus the supersaturation of water vapor required for spontaneous formation of nuclei was measured in a temperature range as wide as possible, namely between $+35^{\circ}$ and -75° .

*"Übersättigung bei der spontanen Keimbildung in Wasserdampf." Die Naturwissenschaften, vol. 31, nos. 39/40, Sept. 24, 1943, pp. 460-465.

¹From the department for motor research of the Hermann Göring Institute for Aviation Research.

²R. Becker and W. Döring, Ann. Physics 24, pp. 719-752, 1935. - M. Volmer, Kinetik der Phasenbildung, p. 200 ff. Dresden-Leipzig 1939.

II. METHOD OF INVESTIGATION AND APPARATUS

The operating principle was as follows: Especially purified air of known pressure, known temperature, and water-vapor content (lying still below saturation) is adiabatically expanded to a certain terminal pressure. During this process cooling off and, also, for a corresponding high expansion ratio, supersaturation occur. If the supersaturation is sufficiently high, fog formation will be observed. The critical supersaturation

$$\left(= \frac{p_1}{p_{\infty}} = \frac{\text{partial pressure of water vapor at the final temperature}}{\text{saturation pressure of water vapor at the final temperature}} \right)$$

is attained when due to the expansion about one fog droplet per cubic centimeter and second becomes visible.

The purification of the initial air and the preadjustment of the water-vapor content were carried out according to the scheme represented in figure 1. This scheme also contains the various methods of operation used. The suspended particles of the initial air could be removed optionally either by a Schott bacteria filter (G5 on 3, fictitious pore diameter according to Bechhold = 1.48μ) or by a layer of absorbent cotton of 100-cm length (it is true that such a layer of only 10-cm length also had proved to be sufficient). The drying was done in two exchangeable freezing traps containing a cotton wool filter of 5-cm length and cooled by liquid oxygen. The water-vapor saturator through which was sent the entire air or only a partial flow line (for the latter case the two flow manometers) consisted of two washing bottles connected in series with adjoining moist cotton wool filter; the entire arrangement was kept at a certain temperature by a Höppler thermostat.

The final adjustment of the water-vapor content was made in the separator as shown in figure 2 which was kept at the same temperature as the observation sphere b proper. The gas flow leaving the separator a, being fully saturated there, was no longer completely saturated later in the expansion sphere b since a pressure drop of about 10-mm Hg appeared in the capillary connecting tubing between a and b at the steady flow velocity of 5-cubic cm/sec used for flushing through and filling.

A methanol bath was used as a cold thermostat which was disposed in a large Dewar vessel (500-mm height, 250-mm inside diameter) with observation strips. The cooling agent was liquid oxygen which was from time to time injected into an immersed glass tube g. The stirring was done mechanically, by means of an electrically driven stirrer of propeller type f.

The temperature measurement was performed with a Hg-thermometer calibrated at the PTR or with a self-manufactured NH_3 -tension thermometer connected to it which was moreover compared with a second model arrangement.

For expansion of the gas under investigation, in the observation sphere b (0.7l) the glass stopcock c (boring 10-mm) was opened quickly toward a large prevacuum vessel (12l) (not shown in figure 2) in which various pressures could be measurably adjusted. In special tests with an expansion sphere of the same size as the observation sphere which contained, however, a metal membrane manometer for mirror reading, it was possible to determine with the aid of films that the expansion time lasted about 0.1 second and the subsequent time of constant pressure more than 0.3 second. No gas vibrations were observed with the connecting tubing used (about 2-m length and 20-mm inside diameter) between expansion sphere (0.7l) and prevacuum vessel (12l).

The observation sphere was coated on the outside with a black lacquer (graphite + vinidur adhesive solution PC 20) in order to keep off scattered light. The illuminating light ray came from an arc lamp through a lens system, entered from below into the observation sphere b through the observation strips of the Dewar vessel and was lost in the expansion cock c. In the first tests, we had operated with a small film projector. However, the intensity of light of that projector was found to be too slight to recognize reliably the condensate particles which are extremely small just at low temperatures. The observation was made obliquely from above through the observation strips of the Dewar vessel.

The content of ions of the expansion gas was either the natural one or it had been reduced to zero in the customary manner, by applying a field of about 50 volt/cm. For this purpose, two opposite inner segments of the observation sphere had been silver-plated and connected with four B-batteries in series (≈ 500 v) by platinum fused through the wall.

The observation sphere as well as the entire remaining apparatus could be pumped out with a low-absolute-pressure aggregate, and could then, after it had been left standing for a while, be examined as to density by means of a Geissler tube.

III. TEST RESULTS

If figure 3, the critical supersaturations measured p_1/p_∞ are represented as a function of the absolute temperature T . Therein p_∞ signifies the saturation pressure of the supercooled water as it was taken from Robitzsch's tables³. Only for the curve branch on the upper right, with a jump at the onset, reference was made to the saturation pressure

³M. Robitzsch, Ausführliche Tafeln zur Berechnung der Luftfeuchtigkeit. Leipzig 1941.

of ice, again using Robitzsch's figures. In order to exclude systematic errors as far as possible the measuring points were obtained by very different methods. There were three possibilities of variation:

(a) The type of air purification and preadjustment of the water-vapor content according to the scheme in figure 1 (marked by capital Latin letters).

(b) The type of final water-vapor content according to the scheme in figure 3 (marked by Roman numerals).

(c) Selection of the initial temperature in the observation sphere so that for a certain expansion end temperature various temperature differences (from 24° to 35°) could be adjusted between center and wall of the sphere.

In figure 3, the measuring points are distinguished only with respect to variation possibility (b). However, none of the methods used for adjustment of the water-vapor content shows any systematic deviations. On the contrary, all measuring points lie so satisfactorily about the solidly drawn curve of mean values that one is quite justified in excluding a falsification of the measured values by insufficient purification of the air (variation possibility (a)) or by insufficiently adiabatic expansion (variation possibility (c)). Only at the lowest temperatures the measuring points show somewhat more scatter the cause of which is, however, in the poor visibility of the condensate particles, reduced more and more with decreasing temperature.

In the temperature region investigated, the critical supersaturations measured p_1/p_{∞} (speed of nucleus formation $J = 1$ particle/cubic cm/sec) can be satisfactorily represented by the following interpolation formulas:

$$\ln \frac{p_1}{p_{\infty}} = \frac{780}{T} - 1.521 \text{ above } -62^{\circ} \text{ without ions}^4 \quad (1)$$

$$\ln \frac{p_1}{p_{\infty}} = \frac{765}{T} - 1.537 \text{ above } -62^{\circ} \text{ with ions}^4 \quad (2)$$

$$\ln \frac{p_1}{p_{\infty}} = \frac{1373}{T} - 3.748 \text{ below } -62^{\circ} \text{ with or without ions}^5 \quad (3)$$

⁴ p_{∞} = saturation pressure of liquid water.

⁵ p_{∞} = saturation pressure of ice.

From the curves in figure 3 one can read off:

1. The influence of the gas ions favoring condensation disappears at -62° .
2. At the same temperature, a break in the supersaturation temperature curve appears, in such a manner that the supersaturation pressures measured at lower temperatures may lie higher but certainly not lower than one should expect on the basis of the curve branch valid at higher temperatures. (Compare the dashed extrapolation curve.)

In addition to these two quantitative findings there is a qualitative one:

3. At very low temperatures, one finds a scintillating of the condensate particles; at -62° it is observable with certainty, at higher temperatures one sometimes imagines seeing it. A rigorous temperature limit for the start of scintillating cannot be defined.

IV. DISCUSSION OF THE TEST RESULTS AND COMPARISON

WITH THE THEORY USED SO FAR

From the quantitative findings 1 and 2, one may conclude that at -62° there starts a more or less sudden change in the spontaneous process of nucleus formation.

The disappearing of the ion influence below -62° would suggest that the nucleus forming at lower temperatures is in a higher order state requiring more space than the nucleus type originating at higher temperatures, for surely the ion influence favoring the condensation must be understood to mean that the water dipoles in the inhomogeneous field of the ion are attracted and tend to arrange themselves as closely as possible around the latter whereby part of the surface work to be expended for nucleus formation is compensated by electrostatic attraction energy. This molecule grouping of maximum density about a central ion will hardly be the molecule arrangement which must take place in ice and thus also in the crystal nucleus as is suggested by the difference in density between water and ice at 0° . It would therefore be understandable if the gas ions would favor the spontaneous formation of crystal nuclei either not at all or at least less than the formation of droplet nuclei.

The scintillating of the formed condensate particles, observed with certainty at -62° , also supports the theory of a primary crystal-nucleus formation although the latter cannot be proved directly by that fact, in our opinion, for a water droplet, too, could suddenly crystallize throughout

after a certain time and be transformed into a scintillating minute crystal. In what time this would be possible under our test conditions, we are not able to tell.

The break in the supersaturation temperature curve found at -62° likewise points at a sudden variation in the process of nucleus formation. However, the direction of this break is strange and in contradiction to the theory used so far. According to Becker and Döring as well as to Volmer⁶ there should always be favored that type of nucleus which requires for its formation the lesser partial pressure in the vapor phase. This conception has the advantage of representing a perfect analogy to the selection of the condensed phase thermodynamically stable in the respective case where, for a prescribed temperature, there always forms the phase which possesses the lower saturation pressure. However, the present report would indicate another process for the formation of the nucleus because of the required partial pressures, for below -62° there would have originated precisely that type of nucleus which requires for its formation a higher water vapor partial pressure than the type of nucleus stable at higher temperature, as one can recognize by comparing the extrapolation curve plotted in dashed lines with the actual measuring points. According to Becker and Döring as well as to Volmer, the break in the supersaturation temperature curve in figure 3, seen from below, should not be convex, but concave; however, this precisely could not be observed within the comparatively high measuring accuracy.

In the theoretical treatment of the spontaneous process of nucleus formation (in absence of ions), Becker and Döring as well as Volmer start out from the same fundamental physical concept: To a vapor molecule, further vapor molecules attach themselves on the basis of the natural fluctuations in successive single steps. Thus aggregates of a higher number of molecules originate each of which may go over into the next highest aggregate by addition of another vapor molecule, into the next lowest aggregate by subtraction of a vapor molecule. The process of nucleus formation itself is interpreted as a stationary chain of reactions so that every aggregate occurs with a certain frequency. Then an expression for the speed of nucleus formation may be derived, in principle, in a simple manner. An explicit evaluation requires, of course, certain simplifying assumptions; they were made in a somewhat different manner by Becker-Döring and by Volmer. We checked their calculations and arrived under the same physical presuppositions of theory but on the basis of a somewhat more accurate calculation at a new formula. It yields numerical values for the speed of nucleus formation which lie between those of Becker-Döring and of Volmer. In the absence of ions, we have therefore for the spontaneous formation of droplet nuclei the following theoretical relations:

⁶Compare especially the figure on p. 202 of his book (cited in footnote 2).

Becker-Döring (\approx to Volmer II)

$$J = \frac{Z_1 W_1 O_1}{n_K} \sqrt{\frac{A_K}{3\pi kT}} e^{-\frac{A_K}{kT}} \quad (4)$$

Volmer I

$$J = \frac{Z_1 W_1 O_K}{n_K} \sqrt{\frac{A_K}{3\pi kT}} e^{-\frac{A_K}{kT}} e^{+\frac{\lambda}{kT}} \quad (5)$$

Sander-Damköhler

$$J = \frac{Z_1 W_1 O_K}{2n_K} \sqrt{\frac{A_K}{3\pi kT}} e^{-\frac{A_K}{kT}} \left[1 - \left(\frac{4}{n_K^{2/3}} - \frac{2}{n_K} \right) \right] \quad (6)$$

Therein signify:

- J number of nuclei formed per cubic cm per second (\approx to the number of fog particles observed per cubic cm)
- Z_1 number of vapor molecules per cubic cm
- W_1 number of vapor molecules impinging per second on 1 square cm at the partial pressure p_1 $\left[W_1 = \frac{N_L p_1}{\sqrt{2\pi MRT}} \right]$
- N_L Loschmidt number ($= 6.0224 \times 10^{23}$)
- R gas constant per g-mol ($= 8.315 \times 10^7$ erg/deg)
- k $R/N_L =$ Boltzmann constant ($= 1.3807 \times 10^{-16}$ erg/deg)
- M molecular weight of the vapor to be condensed
- T absolute temperature
- O_1 surface of the vapor molecule assumed to be spherical
- O_K surface of the droplet nucleus assumed to be spherical which is in equilibrium with the external water-vapor partial pressure p_1

- n_K number of vapor molecules in the drop nucleus ($n_K \approx 100$)
 λ vaporization heat per molecule (for water $\lambda \approx 7.4 \times 10^{-13}$ erg)
 σ surface tension
 A_K $\sigma O_K/3$ = work of nucleus formation
 A_K may, with the Thomson equation

$$\sigma \frac{dO_K}{dn_K} = kT \ln \frac{p_1}{p_\infty} \quad (7)$$

be traced back to the supersaturation p_1/p_∞ wherein p_1 and p_∞ signify:

- p_1 partial pressure of the vapor to be condensed at the temperature T
 p_∞ saturation pressure of the vapor to be condensed at the temperature T

With

$$O_K = Cn_K^{2/3} \quad (8)$$

there follows

$$\frac{A_K}{kT} = \frac{\sigma O_K}{3kT} = \frac{4}{27} \left(\frac{\sigma C}{kT} \right)^3 \frac{1}{\left(\ln \frac{p_1}{p_\infty} \right)^2} \quad (9)$$

For spherical droplets there applies with the condensate density d

$$C^3 = 36\pi \left(\frac{M}{dN_L} \right)^2 \quad (10)$$

and therewith

$$\frac{A_K}{kT} = \frac{16\pi N_L}{3R^3} \left(\frac{M}{d} \right)^2 \left(\frac{\sigma}{T} \right)^3 \frac{1}{\ln \left(\frac{p_1}{p_\infty} \right)^2} \quad (11)$$

According to equations (11) and (4) to (6), there pertains to a certain supersaturation p_1/p_∞ a perfectly defined speed of nucleus formation J . If the latter becomes 1 particle/cubic cm/sec, we obtain the critical supersaturation observed in our measurements which is plotted in figure 3.

In figures 4(a) and 4(b), the experimental supersaturations (in the absence of ions) of the present report are compared to the theoretically calculated curves. For the latter, the numerical values of Moser⁷ were used for the surface tension of water above 0°. They lie highest among the known values of literature⁸ (compare fig. 5) and are probably, for this reason, too, the most correct ones, all the more so because one can very easily lower the surface tension by slight contaminations with surface-active matter, but is hardly able to increase it. Below 0° the surface tension values had to be extrapolated. As may be recognized from figure 4, our new theoretical formula shows the best agreement with our measuring points, at least at and above 0°. Below 0°, however, our first extrapolation of the surface tension values performed at first arbitrarily (curve branch b in fig. 5) yields supersaturations which are too high. We employed therefore the inverse method. Under the assumption that our new formula (6) correctly renders the experimental data in the entire temperature range to -62°, we calculated from them backward the surface tension of the water and obtained thus the curve branch c in figure 5. It is pronouncedly curved; however, in view of the still more pronouncedly cambered curves d and c of Ramsay and Shields and of Weinstein¹⁰ for water, and of the glycerin curve f and g¹¹ (glycerin is also strongly associated) this would not be unthinkable. It is noteworthy that the curve branch c has a maximum for the surface tension of the water at about -50°, that is, not far from the point where the break in the supersaturation temperature curve (compare fig. 3) was found.

⁷Moser, L. B. Eg. IIa, 148.

⁸Compare also Ramsay and Shields, and Weinstein, L. B. I, 199.

⁹The slight differences between experiment and theory above 0° are most probably real and probably based on the fact that in our stationary chain of reactions for excessive water-vapor partial pressure the molecule aggregates exceeding the nucleus size are overheated because the condensation heat cannot be carried off with sufficient rapidity. This point, not yet taken into consideration in the theory used so far, will be discussed more thoroughly elsewhere.

¹⁰L. B. I, 199.

¹¹L. B. I, 255 and L. B. IIa, 156.

For the speed of crystal-nucleus formation Becker and Döring also had derived a formula which is based on the same fundamental physical concepts as the formula for the formation of droplet nuclei. It is true that a considerably larger number of simplifying assumptions was necessary in the derivation of the crystal-nucleus formula because in crystal formation three dimensions may grow independently of each other and an aggregate of n molecules can therefore assume very different shapes, in contrast to the sphere-shaped droplet. The Becker-Döring formula for the speed of crystal-nucleus formation in the absence of ions reads with our above symbols

$$J \approx \frac{1}{3} Z_1 W_1 O_1 \frac{A_K}{kT} e^{-\frac{A_K}{kT}} \quad (12)$$

Therein $A_K = \sigma O_K/3$ represents the work of formation of the solid crystal nucleus. It depends on the interfacial tension between solid and gaseous phase (still unknown at present) as well as on the surface of the determinative crystal nucleus; the form of the latter must be as compact as possible, according to Becker and Döring, but is not exactly defined. For a cube-shaped nucleus (we, too, shall calculate below with such a nucleus) there results from equation (8)

$$C = 6 \left(\frac{M}{dN_L} \right)^{2/3} \quad (13)$$

and hence from equation (9)

$$\frac{A_K}{kT} = \frac{32N_L}{R^3} \left(\frac{M}{d} \right)^2 \left(\frac{\sigma}{T} \right)^3 \frac{1}{\left(\ln \frac{p_1}{p_\infty} \right)^2} \quad (14)$$

One should not overrate the importance of single numerical values obtained with the equations (12) and (14); however, a temperature variation of the critical supersaturation

$$\left(\frac{p_1}{p_\infty} \text{ for } J = 1 \text{ cm}^{-3} \text{ s}^{-1} \right)$$

is significant since equation (12) represents solely the general Arrhenius expression for a reaction velocity with the activation heat A_K which appears perfectly plausible and has been assumed by Volmer for the nucleus formation even before the report of Becker and Doring appeared.

In figure 6, there are plotted as functions of the temperature the saturation pressure of supercooled water (curve a) and of ice (curve b), furthermore the critical supersaturation pressures measured in the present report (curve c) which are required for spontaneous nucleus formation in the absence of ions, and finally the supersaturation curves d_{60} , d_{70} , and d_{80} for the spontaneous formation of ice nuclei calculated with the equations (12) and (14). The arbitrarily assumed interfacial tensions $\sigma = 60, 70$, and 80 erg/square cm between solid and gaseous phase correspond to those supersaturation curves. All curves were based on the saturation pressures of the tables of Robitzsch (footnote 3). One can see that the experimental curve for the supersaturation pressures of the droplet-nucleus formation can be intersected by an ice-nucleus curve in the temperature range investigated only when the interfacial tension of the ice crystals lies approximately between 68 and 72 erg/square cm. If it (the interfacial tension) were independent of the temperature, a convex viewed from the abscissa axis break in the supersaturation pressure temperature curve would never occur but always only a concave one; however, such a concave break is precisely what was not found in the experiment. To explain a convex break, one would have to assume a slight dependence on temperature of the interfacial tension approximately as it is represented in figure 5 as the curve h^{12} .

¹²The temperature coefficient to be read from figure 5, curve h: $-\frac{d\sigma}{dT} \approx 0.062$ erg/square cm degrees is, with respect to order of magnitude, completely in accord with a relation indicated by R. Fricke (Zur physikalischen Chemie, vol. 52, 1942, pp. 284-294)

$$\frac{d\sigma}{dT} = -nk \sum \ln \frac{v_i}{v_a} \quad (15)$$

wherein n = number of molecules per square cm surface, v_i and v_a , respectively = fundamental frequencies of the centers of the molecules vibrating in the interior of the crystal or on the crystal surface, and the summation Σ is to be extended over all lattice vibrations. If one assumes that only one distinguishable lattice vibration is decisive and that the molecules situated on the surface are bound normal to it by about half the spring force as the molecules in the interior of the crystal, there applies

We cannot yet state reliably at present how the break at -62° , indicated by our measuring points in figure 3, is to be explained. Should it be based on the transition of spontaneous droplet-nucleus formation to spontaneous ice-nucleus formation - and we have named indications for this being the case - we would have to give up the prevailing notion regarding the cause of such a transition (that always the type of nucleus forms which requires the least supersaturation pressure). One will give up this concept at first only reluctantly, particularly because of the above-mentioned analogy with the transition from the vapor-water to the vapor-ice equilibrium. Nevertheless this notion entertained so far, regarding the transition of one type of nucleus to the other, does not take into consideration a point which seems to us essential: the mobility of the molecules in the nucleus surface. A droplet nucleus of almost spherical shape can form only if the molecules being newly acquired push in between the surface molecules already present, that is, if they are absorbed by the surface. In the case of a crystal nucleus, in contrast, such a pushing-in need not take place since the molecule being newly acquired, is only added on, that is, in principle, adsorbed. The first process presupposes a considerable mobility of the surface particles, the latter does not. If a sort of two-dimensional melting point existed, that is, if the surface mobility of the particles would suddenly disappear at a certain temperature, no droplet nuclei could form any longer below this

$$\sum \ln \frac{v_i}{v_a} \approx \ln \sqrt{2} = 0.3464$$

since, furthermore, n water molecules

$$n = \left(\frac{6.02 \times 10^{23}}{18} \right)^{2/3} \approx (3.33 \times 10^{22})^{2/3} = 1.033 \times 10^{15}$$

fall to the share of 1 square cm of the crystal surface, one obtains according to (15)

$$-d\sigma/dT \approx (1.033 \times 10^{15}) (1.3807 \times 10^{16}) 0.3464 = 0.0494 \text{ erg/square cm deg}$$

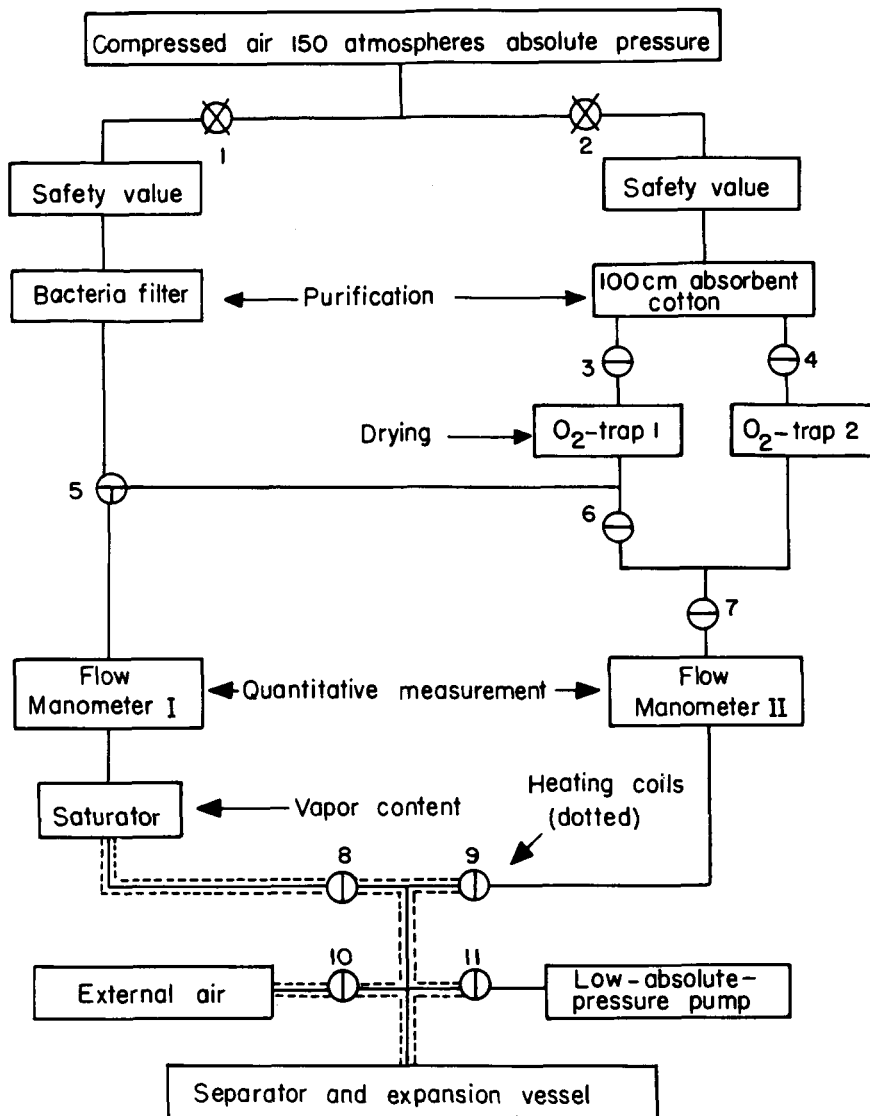
since the tangential frequencies in the crystal surface also will differ somewhat from the corresponding frequencies in the crystal interior, this theoretical value of 0.0494 erg/square cm degree would have to be increased slightly and would then come surprisingly close to our value, inferred experimentally, of 0.062 erg/square cm degree.

temperature and the crystal nucleus would be left as the only primary condensation form, regardless whether the vapor partial pressure necessary for the formation of this crystal nucleus is higher or lower than that of the droplet nucleus. This conception could explain the strange break in the supersaturation temperature curve found by us. Also, this explanation does not perhaps imply an invalidation of the nucleus formation theory used so far but merely limits in a special manner the temperature range of the droplet-nucleus and of the crystal-nucleus formulas. The two regions would not overlap, as was assumed a priori by Becker and Döring as well as by Volmer; rather, the two temperature regions would be separated by the melting point of the two-dimensional surface phase. If we denote it in the absolute temperature scale by T_B , corresponding to the "baking temperature" known from fritting processes and if we denote likewise by T_S the standard three-dimensional melting point, there would result from our measurements $T_B/T_S = 211/273 = 0.77$. This value can probably be fitted into the sequence determined by Tammann¹³.

$T_B/T_S =$	0.33	0.52	0.57	0.90	
	for	metals	oxides	salts	C-compounds

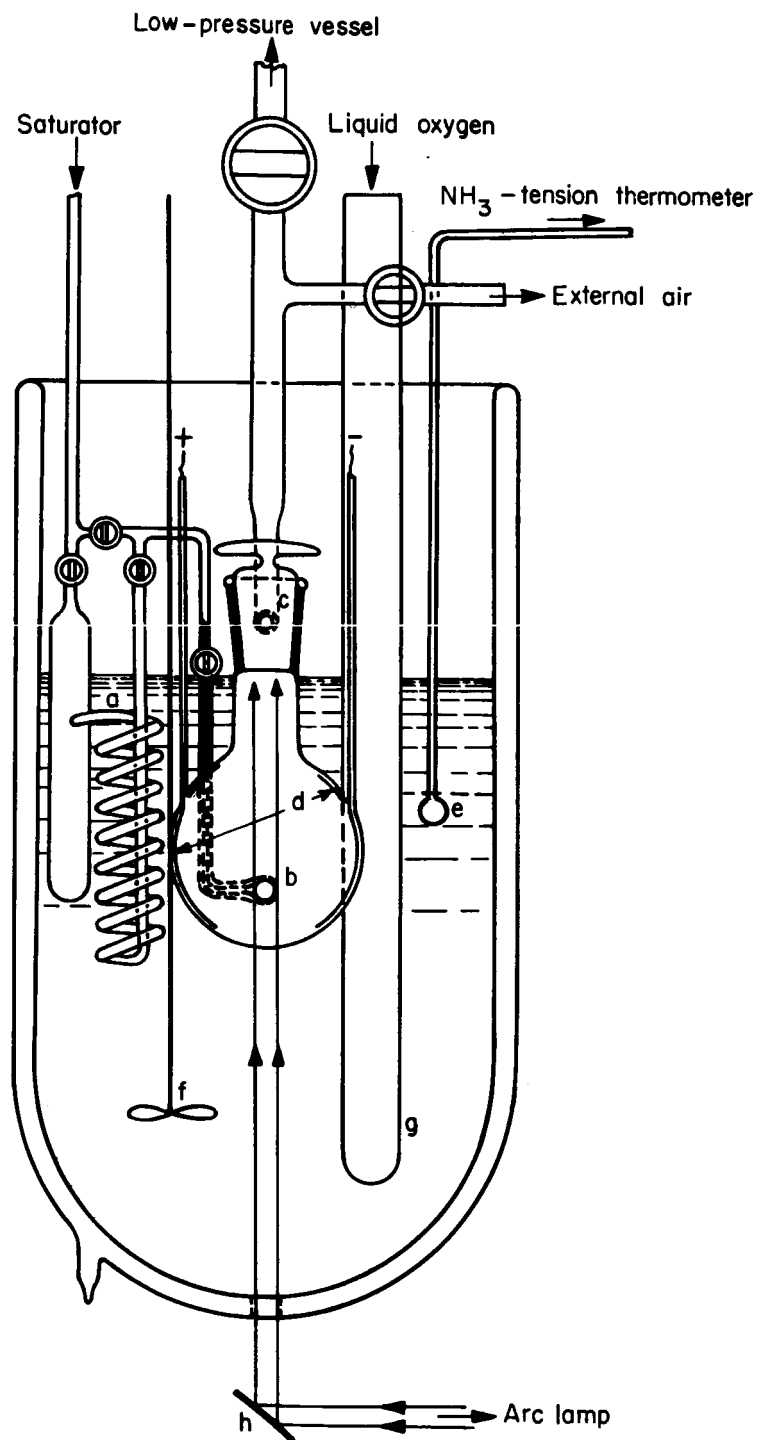
Translated by Mary L. Mahler
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¹³G. Tammann, Z. angew. Chem. 39, 869, 1926 - Göttinger Nachr. Math.-naturwiss. Kl. 1930, 227.



Methods of operation					
	Partial flow line I	Partial flow line II	Position of the stop cocks		
			5	6	7
A	Bacteria filter	Not used	⊕	⊖	⊖
B	100 cm absorbent cotton	Not used	⊕	⊖	⊖
C	Bacteria filter	100 cm absorbent cotton	⊕	(⊕)	⊕
D	100 cm absorbent cotton	100 cm absorbent cotton	⊕	(⊖)	⊕

Figure 1.- Air purification and preadjustment of the water-vapor content.



(a) Separator (b) Observation sphere (c) Expansion stop cock
 (d) Silver plating (e) Feeler of the NH₃ - tension thermometer
 (f) Stirrer (g) Cooling tube (h) Mirror

Figure 2.- Apparatus.

Method of operation	Partial flow lines	Air ahead of separator	Condensate in separator	Condensate in spheres	Symbol without ions	Symbol with ions
I	1 or 2	Too humid	Yes	No	○	●
II	1 or 2	Too dry	Yes	No	○	●
III	1 or 2	Separator not used		Yes	○	●
IV	1	Separator not used		No	○	●
V	2	Separator not used		No	○	●

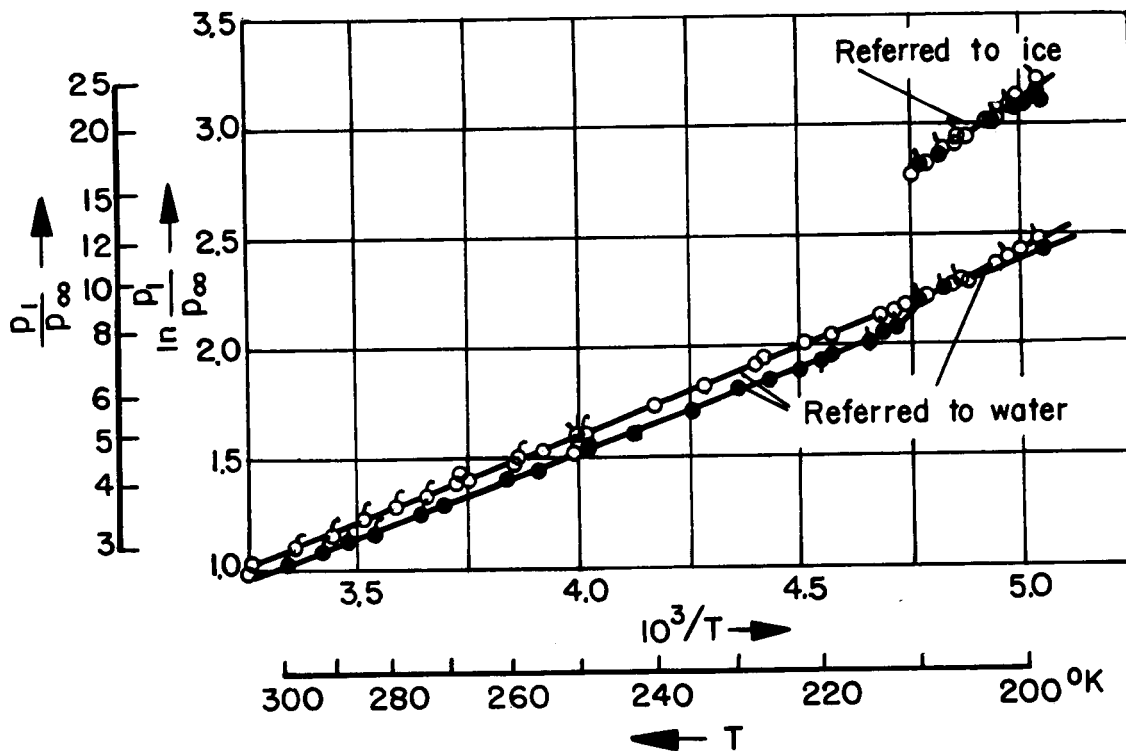


Figure 3.- Water-vapor supersaturations according to tests.

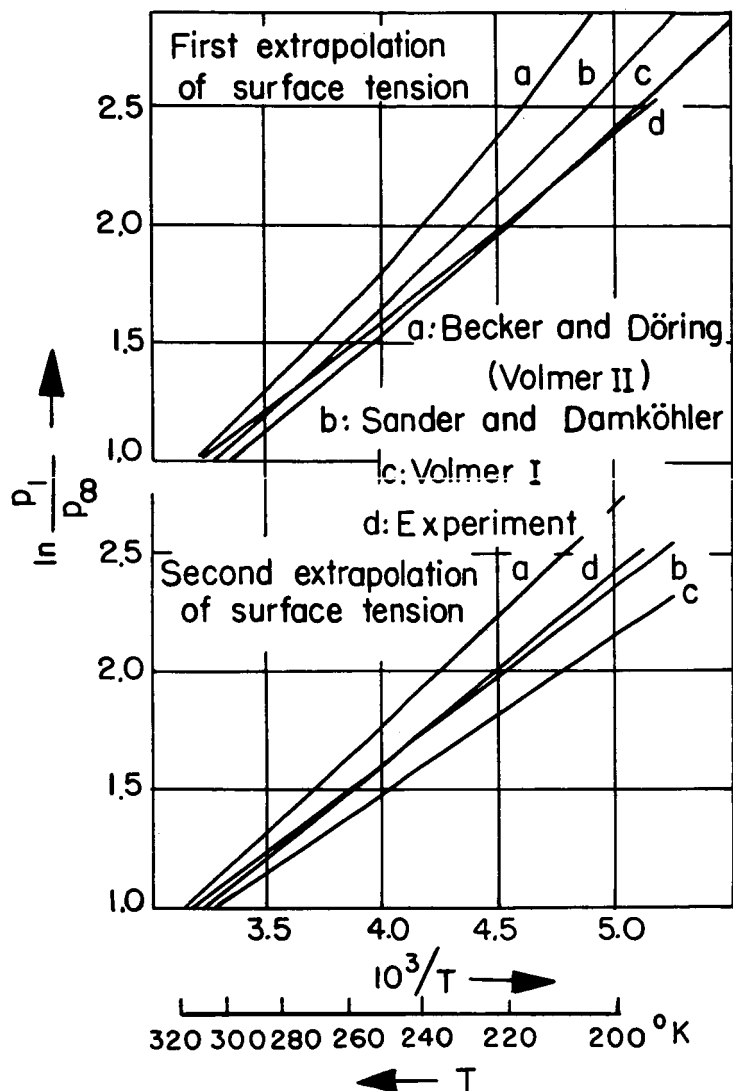


Figure 4.- Theoretical and experimental supersaturation curves for water vapor.

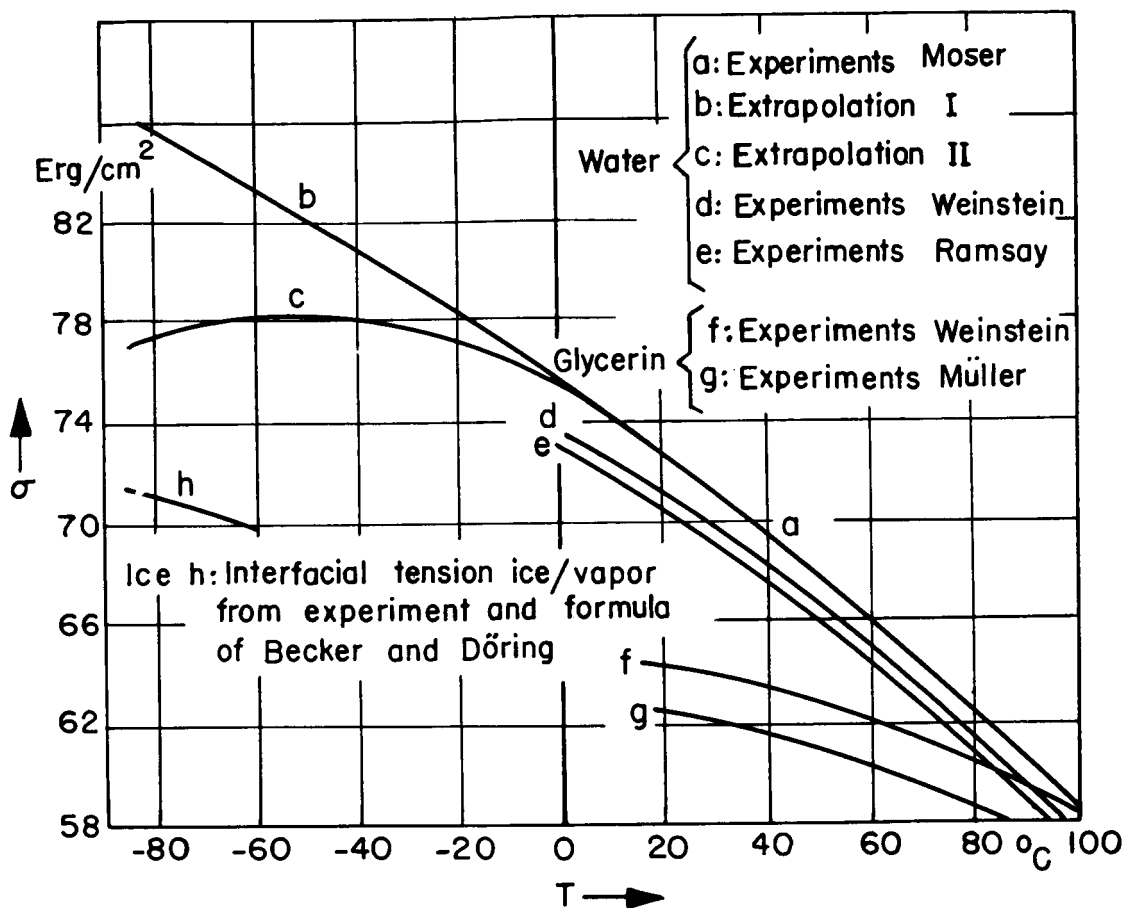


Figure 5.- Surface tension of water, glycerin, and ice.

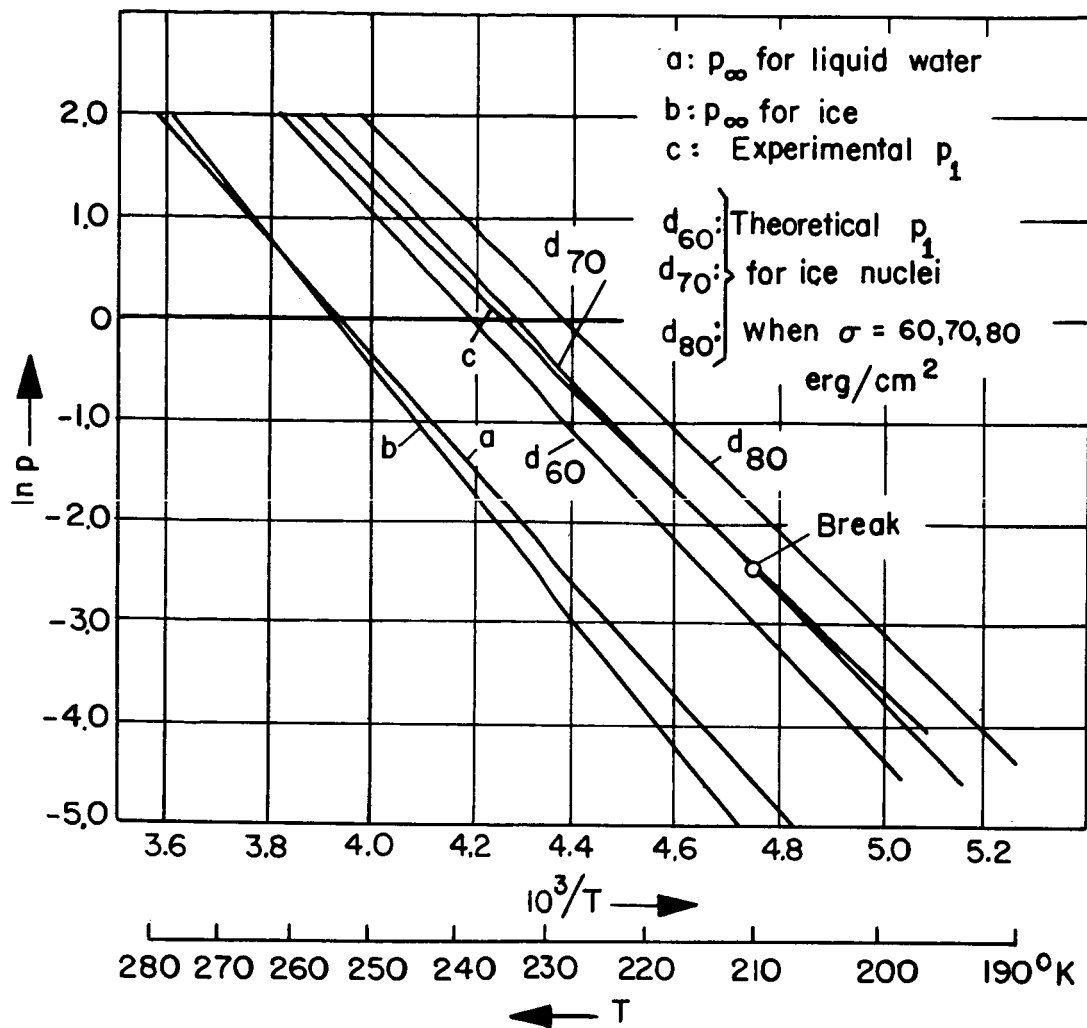


Figure 6.- Saturation pressures (p_{∞}) and supersaturation pressures (p_1) of water vapor.